# Very high-resolution space telescope using the Earth atmosphere as the objective lens

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Telescopes are critical elements of NASA's space program. Very high resolution telescopes are needed to study planets of neighboring stellar systems and life beyond earth. Telescope resolution is limited by aperture diameter but current technology limits telescope apertures to about 10-meters in diameter.

The Earth's atmosphere refracts sunlight such that the sun's image appears about a half degree above its real position during sunset. If we could build a space telescope using the Earth's atmosphere as an objective lens the aperture of such a space telescope would be the diameter of the earth. Telescope resolution could be enhanced by up to seven orders of magnitude and would enable detailed images of planets in far away stellar systems.

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#### 1. Introduction

Since Galileo's first telescope in the 1600s, the telescope has become an essential tool for astronomy and space exploration. Telescope resolution is limited by aperture size. Generally speaking, the larger the aperture, the higher the resolution. Now Hubble Space Telescope (HST) has a diameter of 2.4 meters with resolution of 0.1 arcsecond, and the largest ground based telescope has an aperture of about 10 meters.

NASA now is undertaking a major effort to search for planets in neighboring stellar systems to observe detailed images of these far off planets in the future. A telescope with an aperture diameter in excess of thousands of kilometers could be used to reach such a goal.

It is well known that the resolution of a telescope is limited by its aperture diameter through the equation

 $\Lambda\theta=1.22\lambda/D$ 

Here  $\Delta\theta$  is the angular resolution limit,  $\lambda$  is the wavelength, and D is the diameter of the aperture. For a Jupiter size planet at a distance of 1 pc, the resolution of the

telescope has to be better than  $5x10^{-3}$  arc- second. To detect an earth-like planet at the same distance requires a resolution better than  $3x10^{-6}$  arc-second. A simple calculation shows that to get a direct image of an earth-like planet at a distance of 1 pc, the diameter of a telescope must be hundreds of kilometers; for a detailed image of such a planet, the diameter of a telescope must be thousands of kilometers.

Space interferometry (SIM) may produce images, it does this by combining and processing starlight gathered by those same special mirrors to produce an image, therefore SIM would need thousand kilometers of baseline to produce a high resolution image.

# 2. Earth Atmospheric Space Telescope (EAST)

The Earth's atmosphere refracts sunlight as it passes through the atmosphere. The Earth Atmospheric Space Telescope (EAST) that uses the earth's atmosphere as the objective lens to collect and focus light on a spacecraft borne focal plane<sup>1</sup>. A space telescope using the Earth's atmosphere as the objective lens would provide the necessary resolution to observe other solar systems. The aperture of such a telescope would be the diameter of the Earth, and the resolution would be up to seven orders of magnitude greater than current telescope technology.

The concept for the Earth Atmospheric Space Telescope (EAST) is shown in figure 1. Light from a distance star is almost a parallel beam when reaches the Earth. The Earth's atmosphere refracts the light and focuses it onto a focal plane array in the spacecraft at the left.

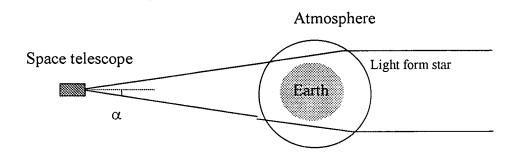


Figure 1. Space telescope using the Earth atmosphere as the objective lens.

The Earth's atmosphere is a huge air shell and can be considered as a lens because it refracts light. Light passing through the atmosphere will be bend and focused somewhere in space. If optics and detectors carried by a spacecraft are placed at the focal plane of the atmospheric lens, a huge space telescope can be constructed. The

entrance pupil is the diameter of the Earth, about 10<sup>8</sup> meters. The resolution of this telescope could be up to 10<sup>7</sup> times higher than Hubble Space Telescope. This telescope has the potential to enable us not only to take direct images of the neighboring planetary systems, but also to view the details of the planets.

Besides very high resolution, the other advantage EAST may have is photon collection efficiency. The earth has a diameter about 120,000 km, and the atmosphere extends to about 200 km above the Earth's surface. Because of its huge size, even if only a small portion of the Earth's atmosphere can be used for imaging, we will be able to collect more photons than the largest telescope.

# 3. Telescope Performance

Because air density decreases with altitude, the focus of an Earth atmospheric lens will not be a single point but will extend over a long line. The shortest focal length f, which is generated by a air shell of atmosphere near the Earth surface, can be estimated as:

$$f == R_0/\alpha$$

here  $R_o$  is the radius of the Earth, and  $\alpha$  is the tilted angle that light bend by the air shell. For a rough estimate,  $\alpha$  is twice of the angle that the sun's image appears about a above its real position during sunset (half degree), therefore,  $\alpha$  is about one degree; take the radius of the Earth is 6400 km, then we can estimate that the shortest focal length is about 370,000 km, roughly the same as the Moon-Earth distance. This provides a unique opportunity to study the EAST concept by looking images generated by the earth atmosphere on the moon during a lunar eclipse.

Optical refraction due to the Earth's atmosphere during a lunar eclipse has been well known since the early 18<sup>th</sup> century. Lahire (1707)<sup>2</sup> found that the earth's shadow projected on the moon exceeded the value given by the theoretical formula. This phenomenon is called the shadow-increase. Cassini (1740)<sup>3</sup> attributed it to refraction by the earth's atmosphereRecently it has been suggested that the earth's atmospheric pollution could be measured by studying the earth's shadow during a lunar eclipse (M. Kocifaj, 1994<sup>4</sup>).

During a total lunar eclipse, Earth based observers can see the moon glowing with a coppery color as it passes through the center of the Earth's umbra. There were several reports about shadow brightening at its center. One of its causes may be the focusing of solar rays onto the center of the auxiliary shadow due to the earth's atmosphere less than 2 km. Another explanation is that in polar regions, refraction is always much greater than at lower latitudes, therefore, as soon as the polar parts of the terminator begin to exert an effort in the vicinity of the center of the shadow, more light than previously begins to penetrate into the center of the shadow and brings about its brightening as polar "windows" (Link, 1948<sup>5</sup> and Svestka, 1949<sup>6</sup>).

The next available total lunar eclipse will be on July 16, 2000. At that time the moon will pass right through the center of the earth umbra, and it will be a good time to observe the details of the sun's image projected on the moon by the atmosphere. Using a high resolution telescope, we can study the focus point distribution of the earth's atmosphere, the size of the focus points, and the stability of the earth's atmosphere as an optical lens.

### 4. Lens Correction

The earth's atmosphere is unstable due to air turbulence, temperature gradient, water vapor etc. If we look at the image of the sun at sunset, it gives us an idea of the atmosphere as an optical system. Actually, the sunset may provide a worst case, because the image is taken from the earth's surface where the atmosphere is most unstable.

Currently the most common method used to correct atmospheric distortion is adaptive optics. Though there was much skepticism whether the technology would ever work, adaptive optics has become a very powerful tool for astronomical observations. Now adaptive optics is used for many big telescopes including the worlds biggest, the Keck telescope. Adaptive optics technology compensates for atmospheric image distortions by measuring the incoming wavefront distortions in real time, computing appropriate correction signals, and driving deformable mirrors or equivalent elements to cancel the distortion. Adaptive optics will be considered to correct for atmospheric distortion in EAST. The wavefront distortion generated by the earth's atmosphere lens would be measured by wavefront sensors, and a deformable mirror would be used for the relay optics on the space telescope to correct the aberration.

The technical design of the EAST may be very different than for current telescopes. Current telescopes have limited entrance pupils, low resolution, low photon collection, but nearly perfect optical systems. But for EAST, it uses the earth atmosphere as the objective lens, has a huge entrance pupil, high resolution, high photon collection, but a very unstable objective lens. How to design the optical system poses an interesting challenge.

#### 5. Conclusion

Compared to current telescopes, EAST will have big advantages in resolution and better photon collection, but there are some technical issues that must be resolved. The density of the atmosphere decreases with the altitude hence the index of refraction is a function of the altitude. The Earth's atmosphere is unstable, wind, turbulence, temperature gradient and water vapor distribution all may have an effect upon optical properties, therefore the optical system design becomes an interesting challenge.

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